

Resonant enhancement of nuclear reactions as a possible solution to the cosmological lithium problem

Richard H. Cyburt^(a,b) and Maxim Pospelov^(c,d)

^(a)*Joint Institute for Nuclear Astrophysics (JINA) <http://www.jinaweb.org>*

^(b)*National Superconducting Cyclotron Laboratory, Michigan State University,
East Lansing, MI, 48824 U.S.A.*

^(c)*Department of Physics and Astronomy, University of Victoria,
Victoria, BC, V8P 1A1 Canada*

^(d)*Perimeter Institute for Theoretical Physics, Waterloo, ON, N2J 2W9, Canada*

Abstract

There is a significant discrepancy between the current theoretical prediction of the cosmological lithium abundance, mostly produced as ${}^7\text{Be}$ during the Big Bang, and its observationally inferred value. We investigate whether the resonant enhancement of ${}^7\text{Be}$ burning reactions may alleviate this discrepancy. We identify one narrow nuclear level in ${}^9\text{B}$, $E_{5/2+} \simeq 16.7$ MeV that is not sufficiently studied experimentally, and being just ~ 200 keV above the ${}^7\text{Be}+d$ threshold, may lead to the resonant enhancement of ${}^7\text{Be}(d, \gamma){}^9\text{B}$ and ${}^7\text{Be}(d, p)\alpha\alpha$ reactions. We determine the relationship between the domain of resonant energies E_r and the deuterium separation width Γ_d that results in the significant depletion of the cosmological lithium abundance and find that $(E_r, \Gamma_d) \simeq (170 - 220, 10 - 40)$ keV can eliminate current discrepancy. Such a large width at this resonant energy can be only achieved if the interaction radius for the deuterium entrance channel is very large, $a_{27} \gtrsim 9$ fm. Our results also imply that before dedicated nuclear experimental and theoretical work is done to clarify the role played by this resonance, the current conservative BBN prediction of lithium abundance should carry significantly larger error bars, $[{}^7\text{Li}/\text{H}]_{\text{BBN}} = (2.5 - 6) \times 10^{-10}$.

1 Introduction

The enhancement of nuclear reaction rates by nuclear resonances is extremely important in nuclear astrophysics, as was first brilliantly demonstrated by Hoyle in the early 1950-s. The remarkable prediction of the 7.65 MeV resonance in ^{12}C not far from the $^8\text{Be} + ^4\text{He}$ separation threshold was based on the consideration of the carbon abundance. The subsequent experimental discovery of this level was one of the defining moments in nuclear astrophysics, and catalyzed further experimental and theoretical work in that area of science [1]. More than half a century after this memorable chapter in the history of physics, it is tempting to speculate whether "history can repeat itself". In this paper we consider a possibility that resonant enhancements of nuclear reaction rates could be responsible for the solution of the so-called cosmological lithium problem.

The problem with the ^7Li abundance came to light during the last decade, as the fast experimental progress in cosmology, and in particular with detailed studies of the anisotropies in the cosmic microwave background (CMB) allowed to sharpen the determination of many cosmological parameters. Currently, among one of the best known parameters is the ratio of the baryon and photon number densities, $\eta_b^{WMAP} = (6.23 \pm 0.17) \times 10^{-10}$ [2]. Since η_b is the main cosmological input into the standard theory of primordial nucleosynthesis (BBN) [3], the uncertainties in predictions of primordial helium, deuterium and lithium abundances shrank to unprecedented levels. In particular, the quality of the comparison of the predicted helium mass fraction Y_p and primordial deuterium abundance with observations mostly depends on the errors in extracting the primordial fractions for these elements from observational data. Currently, there is no disagreement between the predicted and observationally extracted primordial abundances of these two elements.

In contrast to the helium and deuterium abundances, predicted and observed lithium abundances exhibit a serious discrepancy. Its primordial fraction is inferred from the observations of the lithium absorption lines in the atmospheres of population II stars, where as function of metallicity (at low metallicity), lithium exhibits remarkable constancy, known as the Spite plateau [4]. Extrapolation of the Spite plateau to zero metallicity is believed to reflect the primordial value of lithium. Current status of the lithium problem can be summed as follows:

$$\text{Spite plateau value : } \frac{{}^7\text{Li}}{\text{H}} = 1.23_{-0.16}^{+0.34} \times 10^{-10} \quad (1.1)$$

$$\text{BBN theory : } \frac{{}^7\text{Li}}{\text{H}} = 5.24_{-0.67}^{+0.71} \times 10^{-10}, \quad (1.2)$$

where we use the results of evaluation of lithium abundance in field stars [5] and the latest theoretical BBN evaluation [6], both shown as 68% confidence limits ([5] 95% error reduced by half for 68% confidence). It is important to keep in mind that measurements of lithium in globular clusters have resulted in somewhat higher abundances $(2.19 \pm 0.28) \times 10^{-10}$ [7] (for other observational determinations of ^7Li abundance consistent with [5, 7] see [8, 9]). Although there were some claims that the re-calibration of the effective temperature scale is needed that leads to a $\sim 50\%$ increase in the resulting lithium abundance [10], later studies [11] do not find support to this suggestion.

Another interesting twist to the lithium story is added by the claim of the detection of the ${}^6\text{Li}$ metallicity plateau at ${}^6\text{Li}/\text{H} \sim O(10^{-11})$ level, which almost certainly implies some form of pre-galactic ${}^6\text{Li}$. The significant presence of ${}^6\text{Li}$ would also have serious implications for any stellar mechanism that is able to deplete ${}^7\text{Li}$, as ${}^6\text{Li}$ is more fragile and is destroyed at lower temperatures. The status of ${}^6\text{Li}$ plateau claim so far remains in doubt, as subsequent more conservative analyses found no evidence for the plateau [12]. At this point, it is fair to say that only ${}^7\text{Li}$ presents a serious conflict between standard cosmology and observations.

There are several logical possibilities of how the ${}^7\text{Li}$ discrepancy can be resolved that are actively discussed in the literature. It is plausible that the resolution of the lithium problem could involve astrophysical effects, nuclear physics effects or completely new effects in particle physics or cosmology, or any combination of the above. Below we outline some work that has been done in these directions:

- *Astrophysical resolution.* It is possible that the cosmological abundance of lithium is altered in the subsequent evolution. Most notably, there were suggestions that population II stars themselves deplete lithium [13] through *e.g.* diffusional settling during their main sequence lifetimes. Although such a possibility cannot be excluded, any hypothetical stellar process that depletes lithium by a factor of 2-3 should preserve low scatter along the Spite plateau, and be almost independent on other varying astrophysical parameters such as amount of stellar rotation, variations in temperature, etc.
- *Nuclear physics resolution.* Most of primordial lithium is produced as ${}^7\text{Be}$. It is conceivable that some of the nuclear physics reactions that affect ${}^7\text{Be}$ abundance are mismeasured or miscalculated. Recent analyses of all relevant reaction rates do not support this possibility [14, 15, 16, 17], as most of the important reactions are measured/calculated by several groups. Only a drastic change to some secondary reactions, *e.g.* the enhancement of ${}^7\text{Be}(d,p)\alpha\alpha$ rate by a factor of $O(100)$ over the one in the Caughlan-Fowler compilation, could deplete overall ${}^7\text{Be}$ abundance [15]. The follow-up experiment to check this hypothesis has produced a negative result [18].
- *New Physics resolution.* Less likely at this point, but the new physics resolution of the lithium problem may indeed be contemplated. One example are the decays of heavy meta-stable particles that inject extra neutrons at $T \sim 40$ keV, which enhances the destruction of ${}^7\text{Be}$ [19]. Meta-stable negatively charged particles may also lead to the reduction of lithium abundance through the catalysis of reactions that destroy ${}^7\text{Be}$ [20]. Other, more radical ideas include the variation of the strong interaction coupling in time along with modification of the gravitational sector [21]. If indeed the resolution of the lithium problem is related to the meta-stable charged weak-scale particles, there is some hope of testing such hypothesis at the LHC.

We would like to emphasize that the search for the origin of ${}^7\text{Li}$ discrepancy is extremely important for the consistency of modern cosmology. It may hold a clue for the modification of the standard cosmological framework, or at the very least lead to a new level of understanding of physical processes in stellar atmospheres.

In this paper we revisit the possibility that nuclear physics is responsible for the current discrepancy, and investigate whether the primordial value for ${}^7\text{Li}+{}^7\text{Be}$ can be reduced. Unlike Ref. [15], that introduced arbitrary rescaling factors to the reaction rates, we take a different approach, having a closer look at the resonances involved in many reactions. Giving credit to the 50 years of progress in nuclear astrophysics since Hoyle’s discovery, we are *not* going to hypothesize any new resonances, but explore the possibilities that the existing identified resonances could lead to the ${}^7\text{Be}$ depletion. In the next section, we list the resonances that are known to affect ${}^7\text{Be}$ abundance or have some, perhaps remote, possibility of affecting it. We then analyze whether the enhancement of their strength is possible and find one candidate, the 16.7 MeV resonance in ${}^9\text{B}$ that can lead to the enhancement of the ${}^7\text{Be}$ burning in reaction with deuterium. In section 3, we modify the BBN code to include this resonance, and determine the parameters of the resonance that are required to achieve the concordance of the BBN output with the Spite plateau value. We find that indeed such adjustment is theoretically possible, albeit at the very end of the reasonable range for the maximally allowed deuterium separation widths. Section 4 contains the assessment of the uncertainty of the BBN-predicted value for ${}^7\text{Li}+{}^7\text{Be}$, given the uncertainty in the property of this resonance. It also calls for direct experimental determination of the properties of this resonance, and the corresponding reaction rates. These future efforts might either support our hypothesis thus offering a nuclear physics solution to the lithium problem, or refute it, closing perhaps the last nuclear ”loophole” in the BBN prediction of lithium abundance.

2 Nuclear resonances affecting lithium abundance

The 2004 re-analysis of nuclear rates [16] have produced the following scaling relation for the predicted total value of lithium for the WMAP-I input value of η_b :

$$10^{10} \frac{{}^7\text{Li}}{\text{H}} = 4.364 \left(\frac{\eta_b}{6.14 \times 10^{-10}} \right)^{2.12} \left(\frac{\tau_n}{\tau_{n,0}} \right)^{0.44} \left(\frac{G_N}{G_{N,0}} \right)^{-0.72} \\ \times r_2^{1.34} r_9^{0.96} r_8^{-0.76} r_{11}^{-0.71} r_4^{0.71} r_3^{0.59} r_6^{-0.27}. \quad (2.3)$$

Here r_i are the reaction rates R_i in the nomenclature of Ref. [16], normalized on the 2004 recommended reaction rates. Besides reaction rates and η_b dependence, (2.3) also contains the neutron lifetime and Newton’s gravitational constant, normalized to their measured values.

As it is well known, at the CMB-determined baryon asymmetry most of lithium is produced as ${}^7\text{Be}$. The most important temperature range is $T_9 \simeq 0.3 - 0.6$ ($T_9 \equiv T/10^9\text{K}$) where the main production and destruction mechanisms are as follows:

$$\text{Production, } R_9 : \quad {}^3\text{He}(\alpha, \gamma){}^7\text{Be} \quad (2.4)$$

$$\text{Destruction, } R_{11} + R_{12} \quad {}^7\text{Be}(n, p){}^7\text{Li}; \quad {}^7\text{Li}(p, \alpha){}^4\text{He}. \quad (2.5)$$

Recent progress in re-measuring [22] and re-analyzing [23] R_9 , the rate for reaction (2.4), allowed to bring the total uncertainty in the production rate below the 10% level, and together with a revised determination of η_b led to a slight increase in the predicted lithium

Resonance	Reactions	$E_r[\text{keV}]$	$\Gamma_{cm}[\text{keV}]$
np , ground state of 1S	$R_2 : n(p, \gamma)d$	$\simeq 67$	~ 40
^5Li , $3/2^+$, 16.87 MeV	$R_8 : ^3\text{He}(d, p)^4\text{He}$	$\simeq 210$	$\simeq 270$
^8Be , 2^- , 18.91 MeV	$R_{11} : ^7\text{Be}(n, p)^7\text{Li}$	$\sim 10 - 20$	$\simeq 120$

Table 1: Well known resonances that affect lithium abundance.

abundance, Eq. (1.2). Other important parameters that regulate total ^7Be abundance is the availability of free neutrons, the abundance of ^3He at $T_9 \simeq 0.5$, and the neutron capture rate on ^7Be . The abundance of ^3He and availability of neutrons do depend of course on the reaction rates among $A \leq 4$ elements, as reflected in (2.3). It is important to emphasize that all the reaction rates in (2.3) are known with better than 10% accuracy at BBN temperatures.

We now proceed with listing the important resonances that regulate some of the reaction rates in (2.3). We choose to list only those resonances that have resonant energies one the order of 300 keV or less, so that they are important at BBN energies. We organize them in Table 1, where we follow the compilation of Ref. [24] and [25]. The first reaction in this table has an important contribution from the virtual level in the singlet combination of np . It controls the deuterium bottleneck, the temperature relevant for lithium production. The resonance in ^5Li controls the reaction R_8 which depletes ^3He , reducing its availability for the α -capture. Finally, the charge-exchange reaction on ^7Be occurs right at the resonance in ^8Be . In addition to those listed in Table 2, there is also, of course, a well-known resonance in ^5He , $3/2^+$, with $E_X = 16.84$ MeV that dominates the rate R_7 for the reaction $^3\text{H}(d, n)^4\text{He}$ with resonant energy being ~ 50 keV. It provides a secondary source of neutrons at $T_9 \simeq 0.5$. It is also worth mentioning that the rate for R_6 , $^3\text{He}(n, p)^3\text{H}$, is dominated by the sub-threshold resonance in ^4He . It is remarkable that any $O(1)$ variation in either resonant energy or the widths of these resonances would translate to a similar order change in the total ^7Be abundance, Eq. (2.3). Fortunately, at this point all these reactions are very well known, both theoretically and experimentally, and any $O(1)$ changes to their rates within the realm of standard physics are simply not possible.

An interesting side remark is that a hypothetical possibility for reducing ^3He abundance via the resonant enhancement of $^3\text{He}(^3\text{He}, \alpha)pp$ reaction has been actively explored thirty years ago as a possible solution to the solar neutrino "under production" problem [26]. No additional resonances in ^6Be and consequently no additional depletion of ^3He were found [27], and this conclusion can be directly carried over to the BBN calculation. In general, now well-measured neutrino flux summed over flavors agrees with the calculated abundances of ^3He in the Sun, which gives an indirect support to the BBN calculations of ^3He abundance.

We now proceed to searching for additional resonances in the secondary reactions, not included in [16]. These are the reactions of direct burning of ^7Be by light elements other than n , such as p , d , t , ^3He and α , which therefore should involve resonances in such elements as boron and carbon. The resulting possibilities for resonances found in [25] and [28] are listed in Table 2. Among these resonances, it is immediately clear that the sub-threshold resonance in ^{11}C cannot play any role in the depletion of ^7Be because it is way too narrow, $\Gamma/T \lesssim 10^{-7}$. The other two cases cannot be immediately discarded, as there is not enough

Resonance	Reactions	E_r [keV]	Γ_{cm} [keV]
${}^9\text{B}$, $5/2^+$, 16.7 ± 0.1 MeV	${}^7\text{Be}(d, \gamma){}^9\text{B}$, ${}^7\text{Be}(d, p)\alpha\alpha$	~ 200	~ 40
${}^{10}\text{B}$, 2^+ , 18.8 MeV	${}^7\text{Be}(t, \gamma){}^{10}\text{B}$, ${}^7\text{Be}(t, p){}^9\text{Be}$, ${}^7\text{Be}(t, {}^3\text{He}){}^7\text{Li}$	~ 130	< 600
${}^{11}\text{C}$, $3/2^+$, 7.50 MeV	${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$	-43	$< 10^{-4}$

Table 2: Resonances in boron and carbon that could potentially affect lithium abundance.

experimental information about the properties of these resonances. The 16.7 MeV resonance in ${}^9\text{B}$ does appear, however, as a more substantiated hope for reducing ${}^7\text{Be}$ then resonances in ${}^{10}\text{B}$, as the abundance of deuterium at relevant temperatures is much larger than that of tritium, $n_t/n_d \sim 10^{-2}$.

3 16.7 MeV $5/2^+$ resonance in ${}^9\text{B}$ and deuteron-induced reduction of ${}^7\text{Be}$ abundance

Although the direct experimental information about properties of this resonance is not available, something can be learned from the mirror nucleus, ${}^9\text{Be}$. There, the $5/2^+$ resonance at 16.671 ± 8 MeV energy is observed to be extremely narrow, $\Gamma = 41 \pm 4$ keV [29], presumably composed from n , α and γ decay widths. It is reasonable to expect that a mirror resonance in ${}^9\text{B}$ is also narrow. In fact, 40 keV is exactly the width that separate "wide" from "narrow" for the BBN reactions, as the temperature is also about the same value. The possibility of having a resonance with $\Gamma \lesssim T$ is important, as it leads to significant variation of the astrophysical $S(E)$ in the relevant energy range. It is worth mentioning that Ref. [18] made an explicit assumption that $S(E)$ is energy independent below $E \sim 400$ keV. Since we know that the position of this resonance is 200 ± 100 keV above the ${}^7\text{Be} + d$ continuum threshold, one could expect significant variation of $S(E)$ in the relevant energy domain, which in turn may compromise the extrapolation of the measurement [18] to lower energies.

In the absence of direct experimental information, at this point the best strategy is to parameterize the properties of the resonance by some values of the resonant energy, deuteron separation width and total width (E_r , Γ_d , Γ_{tot}). We shall assume that $\Gamma_{tot} \lesssim 40$ keV so that approximation of the reaction rate by a narrow resonance is appropriate. The statistical spin factor for this reaction is $(2 \times \frac{5}{2} + 1)/(3 \times 4) = 1/2$, and the total rate is given by

$$\begin{aligned}
R_{7\text{Be}+d} = & \exp\left(26.429 - 12.5378/T_9^{1/3} - 6.86486T_9^{1/3} - T_9 - 6.T_9^{5/3}\right)/T_9^{2/3} \\
& + \exp\left(40.2944 - 21.1934/T_9^{1/3} - 5.781T_9^{1/3} + 0.14777T_9 - 0.00236773T_9^{5/3}\right)/T_9^{2/3} \\
& + \frac{3.9 \times 10^7}{T_9^{3/2}} \times \frac{\Gamma}{1 \text{ keV}} \times \exp\left(-\frac{2.32}{T_9} \frac{E_r}{200 \text{ keV}}\right),
\end{aligned} \tag{3.6}$$

where the rate is expressed in units of $\text{s}^{-1}\text{cm}^3/\text{mole}$, and $\Gamma \equiv \Gamma_d\Gamma_{out}/\Gamma_{tot}$. Notice that no matter what the actual final state is (other than d), the ${}^7\text{Be}$ nucleus gets destroyed, and therefore we can add different pieces of Γ_{out} together, which for the Breit-Wigner resonance

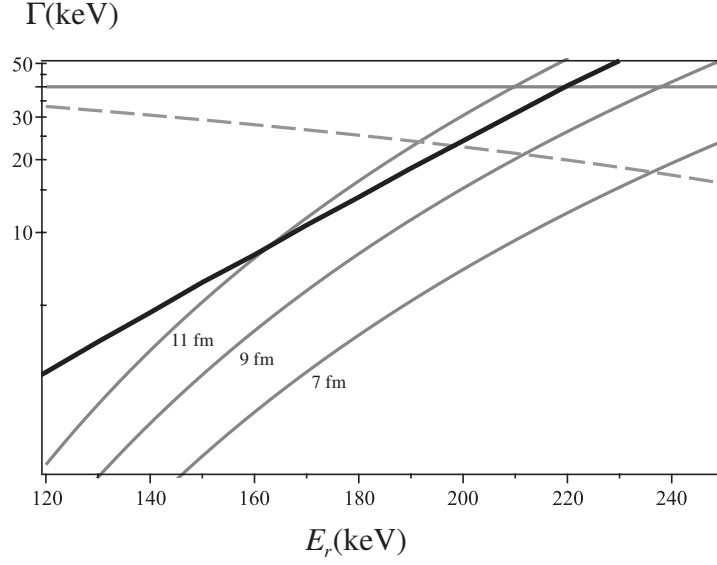


Figure 1: Plotted are the resonance width, Γ in keV vs the resonance energy, E_r in keV. The thick black line corresponds to $\Gamma(E_r)$ at and above which the lithium problem is solved (${}^7\text{Li}/\text{H} \leq 0.5 \times [{}^7\text{Li}/\text{H}]_{\text{SBBN}}$). Three solid diagonal lines are the Wigner limits of Γ for $a_{27} = 7, 9, 11$ fm. The dashed line displays the sensitivity from [18] measurement (with the caveats pointed out in the text).

sums to $\Gamma_{\text{tot}} - \Gamma_d$. To be consistent with the assumption of narrow width approximation, Γ has to be ≤ 40 keV. The non-resonant piece of ${}^7\text{Be}(d, p)\alpha\alpha$ is updated according to [30, 18].

Plugging this rate into the full standard BBN code, we generate an output for ${}^7\text{Be}+{}^7\text{Li}$ as a function of E_r and Γ . In Fig. 1, we invert this calculation and show the curve of the constant depletion factor of 2 relative to the prediction (1.2). One can easily see that on this plot there are regions of parameter space that lead to the factor of 2 depletion of ${}^7\text{Be}+{}^7\text{Li}$ while Γ remains smaller than 40 keV, which would correspond to the solution of the lithium problem by the resonant enhancement of ${}^7\text{Be} + d$ burning. At $E_r \simeq 220$ keV, the required width Γ becomes comparable to the temperature, where our treatment of the narrow resonance is no longer valid. Therefore, we consider 220 keV as an upper value of E_r where the resonant enhancement of ${}^7\text{Be}$ burning is capable of solving lithium problem.

Of course the most important question is whether Γ can reach the level required for the solution of lithium problem. This depends on whether Coulomb suppression of the deuteron separation width Γ_d would preclude $\Gamma \sim O(10)\text{keV}$. The information on mirror nucleus, ${}^9\text{Be}$, is of no use in that respect, because ${}^7\text{Li}+d$ continuum threshold is above the 16.7 MeV $5/2^+$ resonance. Therefore, inevitably one has to invoke some theoretical considerations. As usual we define Γ_d as a product of the Coulomb penetration factor and reduced width γ_d^2 ,

$$\Gamma_d(E_r) = 2\gamma_d^2 P_1(E_r, a_{27}) \lesssim 2\gamma_{dW}^2 P_1(E_r, a_{27}) \equiv \Gamma_{dW}. \quad (3.7)$$

In this expression, $P_1(E_r, a_{27})$ is the deuteron- ${}^7\text{Be}$ p -wave Coulomb penetration factor, a_{27} is the effective radius of the entrance channel, and γ_{dW}^2 is the limiting Wigner expression for the reduced width,

$$\gamma_{dW}^2 = \frac{3}{2\mu a_{27}^2}, \quad (3.8)$$

and $\mu = m_{{}^7\text{Be}}m_d/(m_{{}^7\text{Be}} + m_d)$.

Both the Coulomb penetration factor P_1 and the Wigner limit depend quite sensitively on the channel radius a_{27} , that we keep as a free parameter. Varying a_{27} , we plot the resulting *maximal* Γ_d^{max} on the same plot, as $\Gamma < \Gamma_d^{max}$. One can immediately see that in order to be close to the required strength Γ capable of solving lithium problem, one has to go to the unorthodox values of a_{27} comparable to 10 fm. Nevertheless, Fig. 1 shows that if $a_{27} \gtrsim 10$ fm, the strength the quantum mechanically allowed value of Γ can be above the lithium problem solution line. This may happen only in the narrow limit of energies, $180 \lesssim E_r \lesssim 220$ keV, and Γ will have to be comparable to 10 keV or larger values.

What are the reasonable values for the radius of the entrance channel? A default assumption for a_{27} would be $a_{27} = (2^{1/3} + 7^{1/3}) \times 1.4$ fm = 4.4 fm. This is an unrealistically small value, as both nuclei in question, ${}^7\text{Be}$ and d , are quite large. Another benchmark value is $a_d + a_{{}^7\text{Be}} \simeq 6$ fm. However, previous experience with the deuteron widths of low-lying resonances, in particular with the 16.87 MeV resonance in ${}^5\text{Li}$, suggest much larger interaction radii for ${}^3\text{He} + d$ system [31]. The R -matrix fit to this resonance uses a_{23} to be 5 and 7 fm, finding that for 5 fm the actual γ_d^2 would have to be *above* Wigner limit. Given that $a_{{}^7\text{Be}} > a_{{}^3\text{He}}$ it is then reasonable to allow a_{27} exceed 7 fm. There is however, an ultimate quantum-mechanical limit on a_{27} , coming from the assumption of $a_{27}^2 \sim 1/(E_r\mu)$ scaling. Adopting this scaling, one can find that a_{27} could be comparable to 12 fm for $E_r \simeq 200$ keV, and therefore it is not inconceivable that Γ could reach 10 keV benchmark.

We find that the very fact that there exists a possibility for the nuclear physics solution to the lithium problem via ${}^7\text{Be} + d$ reactions is quite remarkable. If we go to the other possibility, ${}^7\text{Be} + t$, listed in Table 2, we shall discover that no matter what the properties of the 2^+ resonance in ${}^{10}\text{B}$ are, it cannot lead to an appreciable depletion of ${}^7\text{Be}$. Indeed, since the tritium nuclei are less abundant than deuterium by a factor of ~ 100 at relevant temperatures, the required Γ would have to be unrealistically large, comparable to an MeV, and would violate our basic assumption of being a narrow resonance. Therefore, we are forced to discard ${}^7\text{Be} + t$ possibility.

An important question to ask is whether the contemplated resonant enhancement could have been missed in the recent experiment that remeasured ${}^7\text{Be}(d, p)\alpha\alpha$ reaction rate [18]. There is an explicit assumption made in this work that $S(E)$ is the smooth function of energy below 400 keV. This assumption is violated by the 16.7 MeV resonance. Also, Ref. [18] detected only the very energetic protons in the final state, which for example would miss ${}^9\text{B}^* \rightarrow {}^8\text{Be}^* + p$ decays to the 16.63 MeV, 2^+ level in ${}^8\text{Be}$ with the emission of $O(300 - 400)$ keV protons. Ref. [18] argues that such decays will be sub-dominant to the decays into the lower lying states of ${}^8\text{Be}$ because of the Coulomb suppression. This is a valid argument for the continuum but may not necessarily work for the ${}^9\text{B}^*(16.7) \rightarrow {}^8\text{Be}^*(16.63 \text{ MeV}) + p$ transition. Should the decay of 16.7 MeV state in ${}^9\text{B}$ indeed proceed to that level in ${}^8\text{Be}$ the

limits from [18] would simply not apply. There are also other possible final states such as ${}^6\text{Li}+{}^3\text{He}$ and ${}^9\text{B} + \gamma$. In figure 1, we include the dashed line indicating possible sensitivity of [18] to the resonant part of this reaction, but this line should not be treated as a strict upper limit.

Apart from the question of whether or not the lithium problem is solved by the resonant ${}^7\text{Be} + d$ burning, it is important to quantify the error bars in the ${}^7\text{Li}+{}^7\text{Be}$ prediction, as functions of the parameters of the resonance. In what follows, we vary $100 \lesssim E_r \lesssim 300$ keV, and $0 \leq \Gamma \leq \Gamma_{dW}(a_{27})$, and determine the range for the ${}^7\text{Li}+{}^7\text{Be}$ prediction as a function of a_{27} . The results of this procedure are shown in Figure 2. As one can see, the 1σ band gets significantly increased at $a_{27} \sim 9$ fm, and for $a_{27} \sim 12$ fm, a rather wide range of answers is possible,

$$\frac{{}^7\text{Li}}{\text{H}} = [2.5 - 6] \times 10^{-10}. \quad (3.9)$$

Therefore, assuming largest possible a_{27} allowed by quantum mechanics, enlarges the uncertainty in predicting primordial lithium abundance by a factor of more than 2.

4 Conclusions

Nuclear physics could in principle be responsible for the solution of the cosmological lithium problem. Narrow resonances may modify reactions between light elements and affect the abundances of ${}^3\text{He}$ and neutrons at $T \sim 40$ keV that directly affects the outcome of the ${}^7\text{Be}+{}^7\text{Li}$ synthesis. However, the reactions between elements up to helium are well-known directly at BBN energies and the errors on the order of 100% are implausible. It also appears fruitless to hypothesize new previously unknown resonances in these reactions unless some significant experimental mistakes are made at $E_{cm} \sim 50$ keV. Therefore, the only chance of solving ${}^7\text{Be}$ overproduction is the direct destruction of this element by lighter species.

If something destroys ${}^7\text{Be}$ in the early Universe, it is mostly likely by an abundant species, namely neutrons, protons or deuterons. Reactions involving neutrons are known way too well down to very small energies and therefore cannot be a source of error in the BBN calculation. Reaction involving protons, ${}^7\text{Be}(p, \gamma){}^8\text{B}$, is also very well known and its rate cannot catch up with the Hubble rate at $T_9 \simeq 0.5$. The only remaining option are deuterons (tritons are too rare).

In this paper, we have shown that the reaction rates of the ${}^7\text{Be}$ destruction by deuterons could be large, owing to a narrow resonance 16.7 keV, $5/2^+$ in ${}^9\text{B}$ compound nucleus. This resonance may be very strong, and at the very limit of the quantum mechanically allowed value for the deuteron separation width, which would be responsible for a factor of ~ 2 suppression of the primordial ${}^7\text{Be}$ yield, thus resolving the lithium problem. This resonance is presumably somewhat below the range of energies probed by experiment [18], and due to a non-monotonic dependence of S -factor on energy, could have been missed.

If indeed lithium problem is resolved this way, it means that the actual size of $5/2^+$ ${}^9\text{B}$ nucleus is very large, as large as 12 fm, and to a large extent this state should be represented by the p -wave bound state of deuteron and ${}^7\text{Be}$. The width of this state, possibly as narrow

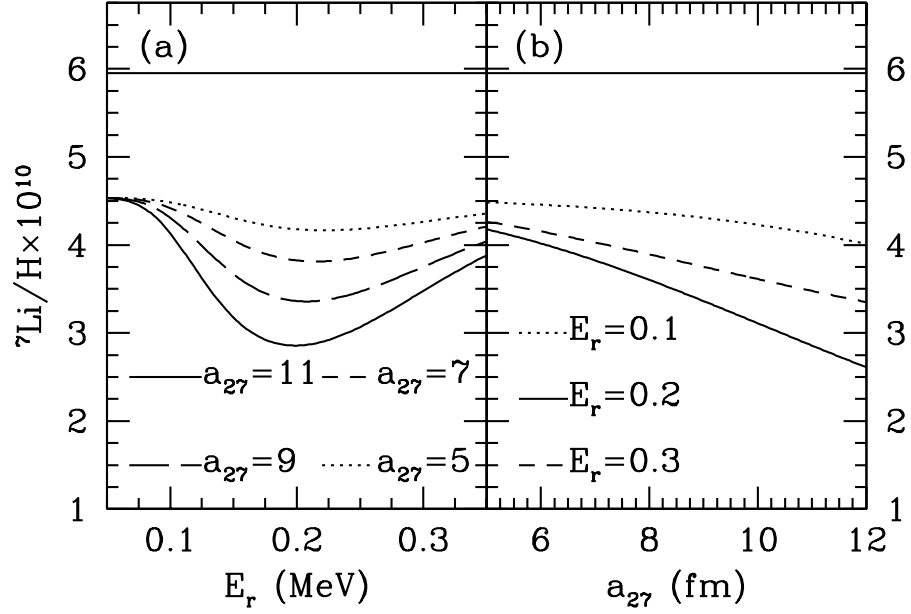


Figure 2: These figures show the standard BBN ${}^7\text{Li}$ abundance predictions allowing for a resonance with energy E_r , with channel radius a_{27} . Figure on the left shows the allowed $1-\sigma$ range for fixed values of the channel radius as a function of the resonance energy). The channel radius lies between 5 and $(200 \text{ keV} \mu)^{-1/2} \sim 12 \text{ fm}$. Figure on the right shows the allowed $1-\sigma$ range for fixed resonance energies as a function of the channel radius.

as 40 keV, should have large contributions from Γ_d , and the rest come from Γ_γ, Γ_p and Γ_α .

In the absence of direct experimental information about this resonance level, and in the absence of dedicated theoretical nuclear studies of its properties, it is of course impossible to declare that this is the solution to the lithium problem. At the same time our study shows that it is premature to rule out the nuclear physics solution to ${}^7\text{Li}$ problem. Only the dedicated study of the $5/2^+$ state in ${}^9\text{B}$ can resolve this issue. Being completely agnostic about the size of the entrance channels, a_{27} , and varying the parameters of the resonance constrained only by quantum mechanics, we find that the error bars in the prediction of lithium abundance should be enlarged, and the whole range $(2.5 - 6) \times 10^{-10}$ is possible.

Finally, we comment on the possibility of experimental test of our hypothesis. There are several experimental possibilities of activating the 16.7 MeV state in ${}^9\text{B}$. Inelastic scattering experiments, such as (e, e') and (p, p') can be used to populate states in the mirror nuclide ${}^9\text{Be}$. Employing isospin symmetry one can gain further insights into the physics of ${}^9\text{B}$ nuclide. One can also use charge exchange reactions on ${}^9\text{Be}$ to populate states in ${}^9\text{B}$, such as the reactions (p, n) and $({}^3\text{He}, t)$. Stripping reactions may also be used to populate this state, via the (p, α) , $({}^3\text{He}, {}^6\text{Li})$ and $(\alpha, {}^7\text{Li})$ reactions on the ${}^{12}\text{C}$ nucleus. Key to these studies would be the use of γ and particle coincidences to tag states.

Acknowledgements

RC would like to thank S. Austin, B.D. Fields, K.A. Olive, H. Schatz and A.W. Steiner for useful discussions. The work of RC was supported by the U.S. National Science Foundation Grants No. PHY-01-10253 (NSCL) and No. PHY-02-016783 (JINA). The work of MP was supported in part by NSERC, Canada. Research at the Perimeter Institute is also supported in part by the Government of Canada through NSERC and by the Province of Ontario through MEDT.

References

- [1] W. A. Fowler, *Nobel Lectures, Physics 1981-1990*, Ed. T. Frangsmyr, G. Ekspang, World Scientific Publishing Co., Singapore, 1993.
- [2] D. N. Spergel *et al.* [WMAP Collaboration], *Astrophys. J. Suppl.* **148**, 175 (2003).
- [3] For a mini-review of BBN see *e.g.*: B. Fields and S. Sarkar in C. Amsler *et al.*, *Phys. Lett. B* **667**, 1 (2008).
- [4] F. Spite and M. Spite, *Astron. Astrophys.* **115**, 357 (1982).
- [5] S. G. Ryan, T. C. Beers, K. A. Olive, B. D. Fields and J. E. Norris, *Astrophys. J.* **530**, L57 (2000).
- [6] R. H. Cyburt, B. D. Fields and K. A. Olive, arXiv:0808.2818 [astro-ph].
- [7] P. Bonifacio *et al.*, *Astron. Astrophys.* **390**, 91 (2002).

- [8] L. Pasquini and P. Molaro, *Astron. Astrophys.* **307**, 761 (1996); F. Thevenin *et al.*, *Astron. Astrophys.* **373**, 905 (2001); P. Bonifacio, *Astron. Astrophys.* **395**, 515 (2002).
- [9] M. Asplund, D. L. Lambert, P. E. Nissen, F. Primas and V. V. Smith, *Astrophys. J.* **644**, 229 (2006).
- [10] J. Melendez and I. Ramirez, *Astrophys. J.* **615**, L33 (2004) [arXiv:astro-ph/0409383].
- [11] A. Hosford, S. G. Ryan, A. E. G. Perez, J. E. Norris and K. A. Olive, arXiv:0811.2506 [astro-ph].
- [12] R. Cayrel *et al.*, arXiv:0708.3819 [astro-ph].
- [13] O. Richard, G. Michaud and J. Richer, *Astrophys. J.* **619**, 538 (2005); A. J. Korn *et al.*, *Nature* **442**, 657 (2006).
- [14] R. H. Cyburt, B. D. Fields and K. A. Olive, *Phys. Lett. B* **567**, 227 (2003) [arXiv:astro-ph/0302431].
- [15] A. Coc *et al.*, *Astrophys. J.* **600**, 544 (2004).
- [16] R. H. Cyburt *et al.*, *JCAP* **0611**, 014 (2006) [arXiv:astro-ph/0608562].
- [17] P. D. Serpico *et al.*, *Int. J. Mod. Phys. A19* (2004) 4431 [arXiv:astro-ph/0307213].
- [18] C. Angulo *et al.*, *Astrophys. J.* **630**, L105 (2005) [arXiv:astro-ph/0508454].
- [19] K. Jedamzik, *Phys. Rev. D* **70**, 063524 (2004) [arXiv:astro-ph/0402344]; R. H. Cyburt, J. R. Ellis, B. D. Fields, K. A. Olive and V. C. Spanos, *JCAP* **0611**, 014 (2006) [arXiv:astro-ph/0608562]; D. Cumberbatch, K. Ichikawa, M. Kawasaki, K. Kohri, J. Silk and G. D. Starkman, *Phys. Rev. D* **76**, 123005 (2007) [arXiv:0708.0095 [astro-ph]].
- [20] M. Pospelov, *Phys. Rev. Lett.* **98**, 231301 (2007) [arXiv:hep-ph/0605215]; C. Bird, K. Koopmans and M. Pospelov, *Phys. Rev. D* **78**, 083010 (2008) [arXiv:hep-ph/0703096].
- [21] V. F. Dmitriev, V. V. Flambaum and J. K. Webb, *Phys. Rev. D* **69**, 063506 (2004) [arXiv:astro-ph/0310892]; A. Coc, N. J. Nunes, K. A. Olive, J. P. Uzan and E. Vangioni, *Phys. Rev. D* **76**, 023511 (2007) [arXiv:astro-ph/0610733]; T. Dent, S. Stern and C. Wetterich, *J. Phys. G* **35**, 014005 (2008) [arXiv:0710.4854 [astro-ph]].
- [22] B. S. Nara Singh, M. Hass, Y. Nir-El and G. Haquin, *Phys. Rev. Lett.* **93**, 262503 (2004); G. Gyurky *et al.*, *Phys. Rev. C* **75**, 035805 (2007); F. Confortola *et al.* [LUNA Collaboration], *Phys. Rev. C* **75**, 065803 (2007); T. A. D. Brown *et al.*, *Phys. Rev. C* **76**, 055801 (2007).
- [23] R. H. Cyburt and B. Davids, *Phys. Rev. C* **78** (2008) 064614 [arXiv:0809.3240 [nucl-ex]].
- [24] D. R. Tilley *et al.*, *Nucl. Phys. A* **708**, 3 (2002).

- [25] D. R. Tilley *et al.*, Nucl. Phys. A**745**, 155 (2004).
- [26] V. N. Fetisov and Y. S. Kopysov, Phys. Lett. B**40**, 602 (1972); Nucl. Phys. A**239**, 551 (1975).
- [27] A. Krauss and H. W. Becker, H. P. Trautvetter and C. Rolfs, Nucl. Phys. A**467**, 273 (1987).
- [28] F. Ajzenberg-Selove, Nucl. Phys. A**506**, 1 (1990).
- [29] S. Dixit *at al.*, Phys. Rev. C**43**, 1758 (1991).
- [30] Kavanagh, R.W., 1960, Nucl. Phys., 18, 492.
- [31] F. C. Barker, Phys. Rev. C**56**, 2646 (1997).